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Probing fundamental physics with pulsars

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Abstract. Pulsars provide a wealth of information about General Relativity, the equation of state of superdense matter, relativistic particle acceleration in high magnetic fields, the Galaxy's interstellar medium and magnetic field, stellar and binary evolution, celestial mechanics, planetary physics and even cosmology. The wide variety of physical applications currently being investigated through studies of radio pulsars rely on: (i) finding interesting objects to study via large-scale and targeted surveys; (ii) high-precision timing measurements which exploit their remarkable clock-like stability. We review current surveys and the principles of pulsar timing and highlight progress made in the rotating radio transients, intermittent pulsars, tests of relativity, understanding pulsar evolution, measuring neutron star masses and the pulsar timing array.

Keywords. stars: neutron, gravitation, equation of state

1. Pulsar surveys

A wide variety of successful pulsar surveys are being carried out using most of the major radio telescopes. We summarize the current status and future prospects here.

Parkes The 1.4-GHz multibeam receiver has discovered over 800 pulsars in the past decade (see Lyne 2008). Reanalyses have resulted in a new class of pulsars (McLaughlin et al. 2006; see §3.1) and continue to find new pulsars using new techniques (Keith et al. 2009). New data acquisition systems provide significantly improved sensitivity to millisecond pulsars (MSPs) and are being used to resurvey the sky.

Effelsberg A similar data acquisition system is now being installed on the seven-beam receiver to provide a complementary survey of the Northern sky.

Arecibo Since 2004, Arecibo has been surveying the Galactic plane with a 1400 MHz seven-beam receiver, and currently 50 pulsars have been discovered (Cordes et al. 2006). Among these new discoveries is a double neutron star binary (Lorimer et al. 2006) an eccentric binary MSP (Champion et al. 2008) and a number of RRATs (Deneva et al. 2009). Several hundred pulsars are expected from this survey over the next five years.

Green Bank A 350 MHz receiver has enabled surveys of the Northern Galactic plane (Hessels et al. 2008) and a drift scan survey of over 10,000 square degrees (Boyles et al. 2008), resulting in a combined 60 new pulsars so far, including five MSPs. The number of pulsars found in these surveys should at least double in the next two years.

Giant Metrewave Radio Telescope Surveys at 610 MHz at low (Joshi et al. 2009) and intermediate (Bhattacharya, private communication) latitudes have been successful, but are plagued with severe radio-frequency interference (RFI). A new survey at 327 MHz will cover 1600 square degrees in a better RFI environment, and is expected to detect roughly 250 pulsars and 30 RRATs (McLaughlin, private communication).

2. Principles of pulsar timing

Once a new pulsar is found, it is observed at least once or twice per month over the course of a year. During each observation, pulses from the neutron star traverse

the interstellar medium before being received at the radio telescope, where they are dedispersed and added in phase to form a mean pulse profile. The time-of-arrival (TOA) is defined as the time of some fiducial point on the integrated profile. Since the profile has a stable form at any given observing frequency, the TOA can be accurately determined by cross-correlation of the observed profile with a "template" profile obtained from the addition of profiles from many observations at a particular observing frequency.

The TOAs are first corrected to the solar system barycenter. Following the accumulation of a number of TOAs, a simple model is usually sufficient to fit the TOAs during the time span of the observations and to predict the arrival times of subsequent pulses. The model is a Taylor expansion of the rotational frequency $\Omega = 2\pi/P$ about a model value Ω_0 at some reference epoch $\mathcal{T}_0$. Based on this model, and using initial estimates of the position, dispersion measure and pulse period, a "timing residual" is calculated for each TOA as the difference between the observed and predicted pulse phases.

Ideally, the residuals should have a zero mean and be free from systematic trends. To reach this point, the model needs to be refined in a bootstrap fashion. Early residuals show a number of trends indicating an error in one or more of the parameters, or a parameter not yet added to the model. For further details, see Lorimer & Kramer (2005).

3. Highlights from the past few years

3.1. *Rotating radio transients*

The discovery of the rotating radio transients (RRATs) in a reanalysis of the Parkes multibeam survey data (McLaughlin et al. 2006) demonstrates the wealth of new sources awaiting detection. The radio emission from RRATs is typically only visible for < 1 s per day making them extremely difficult to study. Their detection was made possible by searching for dispersed radio bursts (Cordes & McLaughlin 2003), which often do not show up in conventional Fourier-transform based searches (Lorimer & Kramer 2005).

Since the initial discovery, a significant effort has gone in to searching for and characterizing more RRATs. Nearly 30 are known (Hessels et al. 2008, Deneva et al. 2009, Keane et al. 2009) but only seven have timing solutions, with four of these only recently achieved (McLaughlin et al. 2009). It is clear (Figure 1a), that the RRATs exhibit varied spin-down properties. Recently, Lyne et al. (2009) reported the detection of two glitches in RRAT J1819−1458. While these events are similar in magnitude to the glitches seen in young pulsars and magnetars, they are accompanied by a long-term *decrease* in the spin-down rate, suggesting that it previously occupied the phase space populated by the magnetars. Further observations could confirm this "exhausted magnetar" hypothesis.

McLaughlin et al. (2009) find that the probabilities that the periods and magnetic fields of RRATs and normal pulsars are drawn from the same parent distributions are small ($< 10^{-3}$), with the RRATs having longer periods and higher magnetic fields. This effect appears to be real and not due to a bias against short period objects. The other spin-down derived parameters of normal pulsars and RRATs are consistent.

3.2. *Intermittent pulsars*

Another new class of radio pulsars, reviewed by Kramer at this meeting, are the intermittent pulsars. The prototype, PSR B1931+24 (Kramer et al. 2006a), shows a quasi-periodic on/off cycle in which the spin-down rate increases by $\sim 50\%$ when the pulsar is on. A spectral analysis reveals a persistent periodicity that slowly varies with time in the range of 30–40 days. The pulsar switches off in less than 10 s, a timescale too small for precession and indicative of a relaxation-oscillation of unknown nature. The dramatic change in spin-down rate points to a large increase in the magnetospheric particle outflow

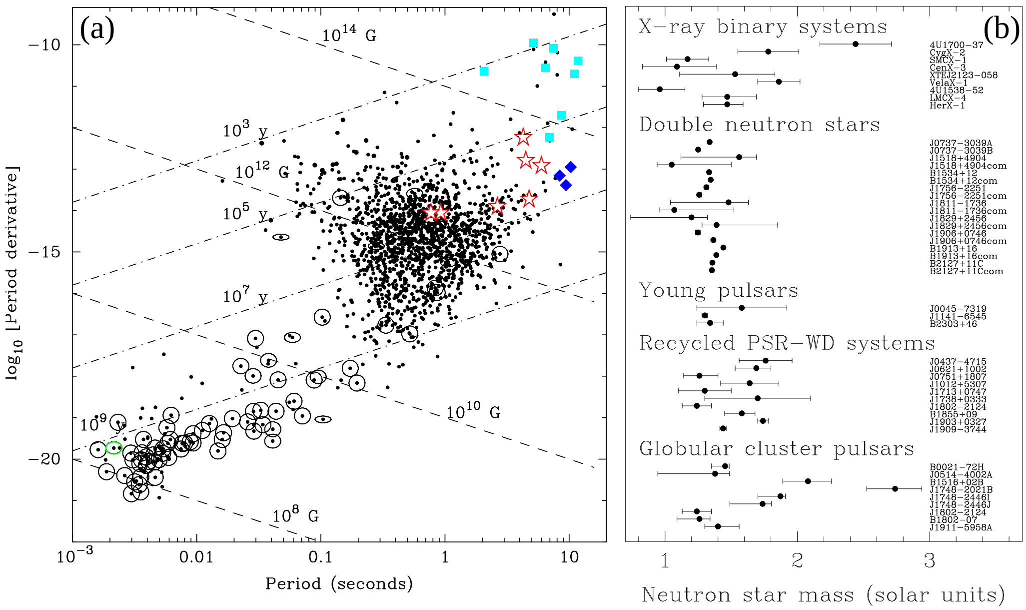

Figure 1. (a) $P - \dot{P}$ diagram of the neutron star population, with radio pulsars as dots, RRATs as open red stars, soft gamma-ray repeaters as blue squares and anomalous X-ray pulsars as cyan triangles. Binaries are marked by circles, with ellipticity equal to that of the orbit and J1903+0327 marked in green. (b) Distribution of neutron star masses as inferred from timing observations of binary pulsars and X-ray binary systems.

when the pulsar switches on. The changes allow us to estimate the current density, which coincides with the predictions by Goldreich & Julian (1969) for pulsar magnetospheres and proves, for the first time, that the pulsar wind plays a substantial role in spin down.

Since PSR B1931+24 is only visible for 20% of the time, we estimate that there should be at least 5 times as many similar objects. Timing archives should be carefully mined to find pulsars with similar characteristics. A number of examples have been found, one of which, PSR J1832+0029, switched off in 2004 after 270 days of consistent detections and switched on again in 2006. Due to this apparent long timescale, we have not yet fully sampled the on/off cycles. RW find the implied magnetospheric charge density for PSR J1832+0029 to be almost four times higher than the Goldreich-Julian density! This cannot be easily reconciled by any of the current models (the debris disks of Cordes & Shannon 2006; the death valley scenario of Zhang et al. 2007 or the accretion model of Rea et al. 2008) and highlights the need for further work.

3.3. *An eccentric millisecond pulsar*

The 2.15-ms pulsar J1903+0327, found in the Arecibo multibeam survey (Champion et al. 2009), is distinct from all other Galactic MSPs in that its 95-day orbit has an eccentricity of 0.43! Optical observations show a possible counterpart which is consistent with a 1 $M_\odot$ star. While similar systems have been observed in globular clusters, presumably a result of exchange interactions, the standard hypothesis in which MSPs are "recycled" via the accretion of mass in a low-mass X-ray binary system cannot account for J1903+0327. A triple system now appears to be ruled out due to the lack of any change in orbital eccentricity in the system (Gopakumar et al. 2009). It is possibile that the binary system was produced in an exchange interaction in a globular cluster and subsequently ejected, or the cluster has since disrupted. Statistical estimates of the likelihood of both these

channels are roughly 1–10%. Finally, as discussed by Liu and Li at this meeting, a scenario involving accretion from a supernova fall-back disk is also viable.

3.4. *Tests of relativity*

Although most binary pulsars can be adequately timed using Kepler's laws, there are a number which require an additional set of "post-Keplerian" (PK) parameters which have a distinct form for a given relativistic theory of gravity (Damour & Taylor 1992). In General Relativity (GR) the PK formalism (see Lorimer & Kramer 2005) gives the relativistic advance of periastron, $\dot{\omega}$, the time dilation and gravitational redshift parameter, γ, the rate of orbital decay due to gravitational radiation, $\dot{P}_{\rm b}$, and the two Shapiro delay parameters, r and s. Some combinations, or all, of the PK parameters have now been measured for a number of binary pulsar systems.

Given the precisely measured Keplerian parameters, the only two unknowns are the masses of the pulsar and its companion, $m_{\rm p}$ and $m_{\rm c}$. Hence, from a measurement of just two PK parameters one can solve for the two masses. From the Keplerian mass function one can then find the orbital inclination angle i. If three (or more) PK parameters are measured, the system is "overdetermined" and can be used to test GR (or any other theory of gravity) by comparing the third PK parameter with the predicted value based on the masses determined from the other two.

As discussed by Kramer's contribution in JD06, currently the best binary pulsar system for strong-field GR tests is the double pulsar J0737−3039. In this system, with two independent pulsar clocks, five PK parameters of the 22-ms pulsar "A" have been measured as well as two additional constraints from the mass function and projected semi-major axis of the 2.7-s pulsar "B". The measurement of the projected semi-major axes gives a mass ratio $R = 1.071 \pm 0.001$. The mass ratio measurement is unique to the double pulsar and rests on the assumption that momentum is conserved. The observations of $\dot{\omega}$ and R yield the masses of A and B as $m_{\rm A} = 1.3381 \pm 0.007\, M_\odot$ and $m_{\rm B} = 1.2489 \pm 0.0007\, M_\odot$. From these values, the expected values of γ, $\dot{P}_{\rm b}$, r and s may be calculated and compared with the observed values. These four tests of GR all agree with the theory to within the uncertainties. Currently the tightest constraint is the Shapiro delay parameter s where the observed value is in agreement with GR at the 0.05% level (Kramer et al. 2006b).

Another unique feature of the double pulsar system is the interaction between the two pulsars. The signal from A is eclipsed for 30 s each orbit by the magnetosphere of B (Lyne et al. 2004) and the radio pulses from B are modulated by the relativistic wind from A during one phases of the orbit (McLaughlin et al. 2004). These provide unique insights into plasma physics. By modeling of the change in eclipse profiles of A over four years, Breton et al. (2008) fit a simple model to determine the precession of B's spin axis about the orbital angular momentum vector. This measurement agrees, within the 13% measurement uncertainty, with to the GR prediction.

3.5. *Massive neutron stars*

Multiple PK parameters measured for a number of binary pulsars provide precise constraints on neutron star masses (Thorsett & Chakrabarty 1999). As shown in Figure 1b (from Lorimer 2008), the young pulsars and the double neutron star binaries are consistent with, or just below, the canonical $1.4\, M_\odot$, but the MSPs in binary systems have, on average, significantly larger masses.

Several eccentric binary systems in globular clusters have their masses constrained from measurements of the relativistic advance of periastron and the Keplerian mass function. In these cases, the condition $\sin i < 1$ sets a lower limit on the companion mass $m_{\rm c} > (f_{\rm mass} M^2)^{1/3}$ and an upper limit on the pulsar mass. Probability density functions

for both m_p and m_c can also be estimated in a statistical sense by *assuming* a random distribution of orbital inclinations. An example is the eccentric binary MSP in M5 (Freire et al. 2008) where the nominal pulsar mass is 2.08 ± 0.19 M$_\odot$. If these can be confirmed by the measurement of other relativistic parameters, these supermassive neutron stars will have important constraints on the equation of state of superdense matter.

Currently the largest measurement of a radio pulsar mass is the eccentric MSP binary J1903+0327 (Champion et al. 2008). Recent timing measurements of the relativistic periastron advance and Shapiro delay in this system by Freire et al. (2009) yield a mass of 1.67 ± 0.01 M$_\odot$. When placed on the mass–radius diagram for neutron stars (Lattimer & Prakash 2007) this pulsar appears to be incompatible with at least four equations of state. Optical measurements of the companion are required to rule out classical contributions to $\dot{\omega}$, and further timing measurements are required to verify this result.

3.6. *Pulsar timing and gravitational wave detection*

As discussed by Andersson at this meeting, the direct detection of GWs is one of the foremost goals of modern physics. Many cosmological models predict that the Universe is presently filled with an ultra low-frequency (nHz) stochastic gravitational wave (GW) background produced during the big bang era (Peebles 1993). A significant component (Jaffe & Backer 2003) is the gravitational radiation from massive black hole mergers due to Galaxy collisions at a redshift $z \sim 1$. Pulsars can be used as natural GW detectors of this background (Sazhin 1978; Detweiler 1979). pulsar acts as a reference clock, sending out regular signals which are monitored by an observer on the Earth over some timescale T. Passing GWs perturb the local spacetime and cause a change in the observed rotational frequency of the pulsar. For regular pulsar timing observations with typical TOA uncertainties of ϵ_TOA, this detector would be sensitive to GWs with amplitudes $h \gtrsim \epsilon_\mathrm{TOA}/T$ and frequencies $f \sim 1/T$ (Bertotti et al. 1983; Blandford et al. 1984).

A natural extension of this concept is a "timing array" of a number of pulsars distributed over the sky (Hellings & Downs 1983), allowing cross-correlation of the residuals for pairs of pulsars (Foster & Backer 1990). It should therefore be possible to separate the timing noise of each pulsar from the common signature of the quadrupolar GW background from the effects of clock errors (which have a monopolar signature) and solar system ephemeris errors (which have dipolar signature).

As reviewed by Manchester in JD06, three main groups are collaborating to form an international pulsar timing array. The European Pulsar Timing Array consists of four radio telescopes which will be combined to produce a 300-m class telescope. In Australia, the Parkes Pulsar Timing Array uses the 64-m Parkes telescope to time Southern pulsars. In North America, the Green Bank and Arecibo telescopes are used in the NANOGrav collaboration. The best existing limits (Jenet et al. 2006) constrain the merger rate of supermassive black hole binaries at high redshift, investigate inflationary parameters and place limits on the tension of currently proposed cosmic string scenarios.

Based on current expectations of the likely strength of the GWB, a detection requires timing of 20 MSPs with 100 ns residuals for a period of five years (Jenet et al. 2005). In general, for residuals δt, data span T, and number of pulsars N, the sensitivity scales roughly as $\delta t^2/(NT^4)$ (Kaspi et al. 1994). Of the $\sim$30 MSPs that are regularly timed internationally, five have achieved a timing precision of 100 ns or less. With improved algorithms and more sensitive observations, such precision may soon be achieved for 5–10 more. A key goal of the ongoing surveys is to find more MSPs to add to the array. This should be accomplished by the various surveys outlined in Section 1, and GW detection may be achievable within the next 5 – 10 years.

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